

DIS2011 Heavy Flavours Session Summary (WG5)¹

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Abstract. We summarize the presentations of the Heavy Flavours working group for the 2011 DIS Workshop. This session contained presentations on theoretical methods and experimental measurements of heavy quark production, and the impact on recent experimental results from HERA, RHIC, Tevatron, and LHC.

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OVERVIEW

The production of heavy quarks in high energy processes has become an increasingly important subject of study both theoretically and experimentally. The theory of heavy quark production in perturbative Quantum Chromodynamics (PQCD) is more challenging than that of light parton (jet) production because of the new physics issues brought about by the additional heavy quark mass scale. The correct theory must properly take into account the changing role of the heavy quark over the full kinematic range of the relevant process from the threshold region (where the quark behaves like a typical “heavy particle”) to the asymptotic region (where the same quark behaves effectively like a parton, similar to the well known light quarks $\{u, d, s\}$).

The experimental measurements of the heavy quarks are also challenging as the heavy quark signal must often be extracted from underneath the dominant light quark process. Nevertheless, the range and precision of the heavy flavor measurements continues to improve and enable incisive tests of the various production mechanisms.

THEORETICAL CHALLENGES

Large momentum transfer production of particles and jets provided some of the early tests of QCD. Indeed, by taking into account quark and gluon initiated scattering processes, QCD was able to explain the relatively large cross sections observed at the CERN ISR. However, as the precision of the experiments increased, there was a corresponding

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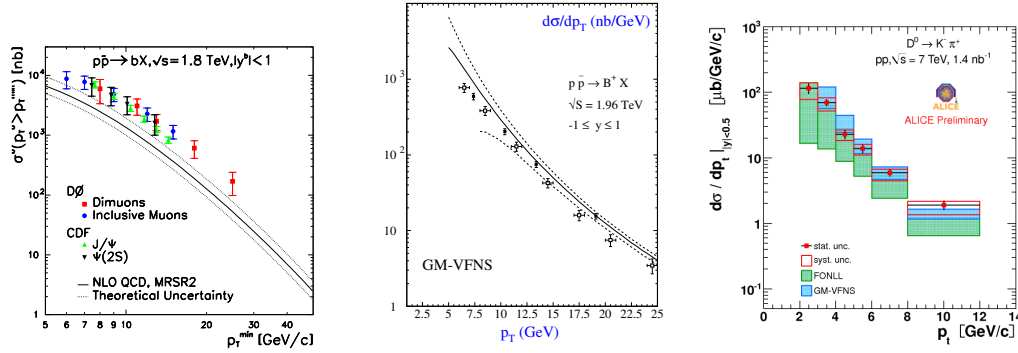


FIGURE 1. a) The status of b-quark hadroproduction circa 1999. b) Updated GM-VFNS analysis of B hadroproduction circa 2011. c) Preliminary D hadroproduction data from the LHC.

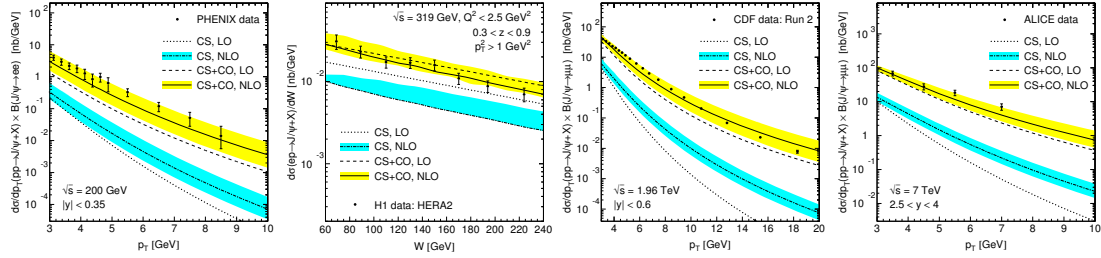


FIGURE 2. J/ψ production for a variety of experiments compared with the Color Singlet (CS), Color Octet (CO), Leading Order (LO), and Next-to-Leading Order (NLO) predictions.

need for increased theoretical precision and discrepancies arose between theory and data for several large momentum transfer processes.

One such long-standing issue in QCD was the calculation of the cross section for the production of b-quarks at high energy hadron colliders. In the 1999 CERN LHC Workshop proceedings (hep-ph/0003142), the integrated transverse momentum spectrum for b production at the Tevatron vs. p_T was a factor of 2 above the NLO theoretical predictions (c.f., Figure 1-a). The resolution of this discrepancy was multifaceted involving improvements on both the experimental and theoretical side; as a result of these improvements, we are now able to find good agreement between the data and theory for these observables.

Bernd Kniehl (in collaboration with G. Kramer, I. Schienbein, and H. Spiesberger) presented updated results on the hadro-production of D and B mesons.[1] They used the General-Mass Variable Flavor Number Scheme (GM-VFNS) calculation with updated fragmentation functions extracted from LEP and B-factory data. Figure 1-b) displays the results for B meson production at the Tevatron, and Figure 1-c) displays the results for D meson production at the LHC. The GM-VFNS employs the full mass dependence in the calculation, and the fragmentation functions include the full scaling violations. The good agreement observed between the data and theory validates this approach and reaffirms our ability to make accurate calculation for all mass scales—from small to large—with this parameter-free formalism.

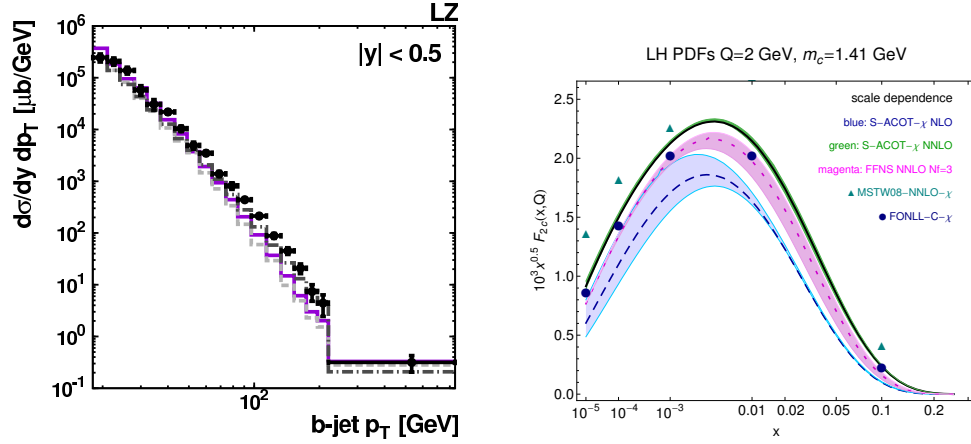


FIGURE 3. a) b-jet p_T differential cross section computed with the CASCADE Monte Carlo generator. b) F_2^c comparisons at NNLO.

In a separate presentation, Bernd Kniehl (in collaboration with M. Butenschon) discussed recent calculations of the cross sections for inclusive J/ψ production at next-to-leading order (NLO) within the factorization formalism of non-relativistic quantum chromodynamics (NRQCD), including the full relativistic corrections due to the intermediate $^1S_0^{[8]}$, $^3S_1^{[8]}$, and $^3P_J^{[8]}$ color-octet states.[2] In this context, they performed a NLO global fit of the respective color-octet long-distance matrix elements to all available high-quality data of inclusive unpolarized J/ψ production, including KEKB, LEP II, RHIC, HERA, the Tevatron, and the LHC, comprising a total of 194 data points from 26 data sets. Selected results are displayed in Figure 2. The fit values of the color-octet (CO) long-distance matrix elements (LDMEs) agree with their previous analysis, demonstrate the validity of NRQCD factorization for charmonium, and provides evidence for LDME universality and the existence of CO processes. Future work on polarized J/ψ production could provide additional information on these terms.

N.P. Zotov (in collaboration with H. Jung, M. Kraemer, A.V. Lipatov) presented predictions from the CASCADE Monte Carlo generator for b-jet and quarkonium production at the LHC.[3] CASCADE uses the k_T -factorization approach with unintegrated (k_T -dependent) gluon distribution (UGD). The UGDs in a proton are determined using the CCFM evolution equation and the Kimber-Martin-Ryskin (KMR) prescription. With conventional PDFs, the exchanged parton is assumed to be on-shell, and collinear with zero k_T . In contrast, the UGD allows for non-zero k_T contributions even at Leading-Order (LO); hence it has the potential to provide an improved description of the physics at a given order in perturbation theory. Results for inclusive b-jet and quarkonium production have been computed in this approach for the CERN LHC energies, and a sample comparison with the CMS data is shown in Figure 3-a). The overall description of the data is reasonable, and in most cases it is comparable to the standard Monte Carlo calculation; notably, there are some distributions where the k_T -factorization approach yields an improved description of the data.

Christian Pascaud presented a new “Continuous Flavor Number Scheme” (CFNS) for heavy flavors in DIS.[4] The goal was to modify the DGLAP evolution to include the

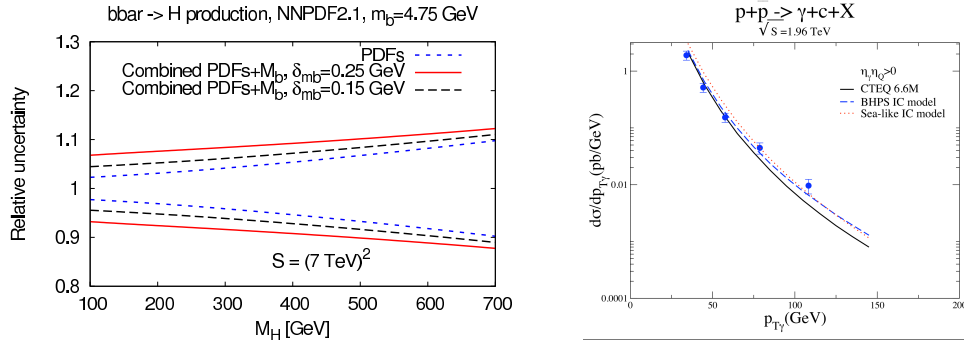


FIGURE 4. a) Combined PDF+ m_b uncertainties (1σ) on the total cross section for $b\bar{b} \rightarrow H$ production. b) The differential cross section for $p\bar{p} \rightarrow \gamma c X$ using the CTEQ6.6M PDFs, and two Intrinsic Charm (IC) models.

heavy quarks at all scales and suppress the heavy flavors at high x in the low Q region based upon the kinematical constraints (i.e., $W > 2M_h$), the momentum sum-rule, and the quark counting sum-rules. Thus, for $Q^2 \ll 4M_h^2$ the corresponding heavy quark is decoupled, while for $Q^2 \gg 4M_h^2$ the DGLAP equations and coefficient functions regain their usual appearance. Comparisons with the conventional schemes were made for both the fitted PDFs as well as the F_2^{cc} structure function.

Nikolaos Kidonakis presented new results on the top quark cross section and differential distributions.[5] Specifically, results for $t\bar{t}$ and single top production channels performed at NNLL resummation were presented. The resummed NNLL calculation results in reduced scale dependence of the cross section as compared to the lower order results. Additionally, the enhancements due to the NNLO approximation are significant as compared to the NLO results. For the $t\bar{t}$ channel at the LHC the enhancement is +7.6% at $1\sqrt{s} = 7$ TeV and +8.0% at $\sqrt{s} = 14$ TeV. Similarly, For single top at the LHC the shift is -1% to -3% in the t -channel, and +13% in the s -channel. These processes are precision “standard candle” measurements for the LHC and also can serve to calibrate the Higgs search.

F. Wissbrock (in collaboration with J. Ablinger, J. Blumlein, S. Klein, and C. Schneider) presented the first results for 3-Loop Heavy Flavor Corrections to DIS with two Massive Fermion Lines.[6] Specifically, these are the contributions at order $\mathcal{O}(\alpha_s^3)$ which are proportional to $T_F^2 C_{FA}$. This calculation is part of a broader program to extend the analysis of the PDFs to NNLO order while retaining the massive contributions.

M. Guzzi (in collaboration with P. Nadolsky, C.-P. Yuan, and H.L. Lai) presented preliminary results on the S-ACOT- χ heavy flavor contributions at NNLO.[7] This also is a key ingredient for extending the PDF analysis to higher order in the perturbation theory. Preliminary results (sample shown in Figure 3-b) indicates that this approach for the NNLO calculation of $F_2^{c,b}$ and $F_L^{c,b}$ is viable, and the NNLO predictions are stable, exhibit reduced scale dependence, and will minimize the “tuning” of both the m_c and the ξ -scaling parameter. S-ACOT- χ is the default heavy-quark scheme of CTEQ PDF analyses and it will play a significant role in global fits at NNLO.

S. Alekhin (in collaboration with S. Moch) presented the a new calculation which implemented the running mass definition for the DIS semi-inclusive structure function.[8]

The goal of this approach is to obtain improved perturbative stability with reduced scale variation, and a better determination of the heavy quark PDFs. Comparisons with the HERA data for F_2^{cc} are presented and yield good agreement. Additionally, the extracted value of the charm mass compares favorably with the PDG value.

R. Placakyte (on behalf of the H1 and ZEUS collaborations) presented a study of the combined H1 and ZEUS F_2^{cc} data investigating the effects of the renormalization scheme and the charm mass.[9] By treating the charm mass as a free parameter and allowing the fit to select an optimal value, they discovered that different schemes yield very different values for the charm mass. They then studied the impact of these differences for W production at the LHC. Remarkably, they find that if the schemes and charm mass values are implemented consistently, the net effect on the predicted W boson production cross section is largely compensated so that the total uncertainty is roughly 1%; in contrast, the uncertainty associated with a straightforward variation of the charm mass can be as much as 5%. Thus, the use of the optimal charm mass serves to reduce the uncertainty of the cross section predictions.

J. Rojo (on behalf of the NNPDF collaboration) investigated the impact of the heavy quark mass on the PDFs.[10] Specifically, he presented a new fit (NNPDF2.1) which was performed in a General-Mass Variable-Flavor-Number (GM-VFN) scheme, and compared this to the Zero-Mass result (NNPDF2.0). The two sets of PDFs were consistent at the 1σ -level, and most of the differences arose at medium to small x values. To see the impact on physical observables, they studied the sensitivity of the W and Z cross sections; for charm mass variations in the range [1.4, 1.7] GeV, they find the variation of the cross section is generally at the 1σ -level or less. The variation of the b-quark mass could be important for b-quark initiated processes such as $b\bar{b} \rightarrow H$ or t-channel single-top production. Figure 4-a) displays the relative uncertainty of the Higgs production cross section combining the PDF uncertainty with the corresponding uncertainty on the b-quark mass; this can grow as large as 10% for large Higgs mass values.

K. Kovarik (in collaboration with T. Stavreva, I. Schienbein, F. Arleo, F. Olness, J. Owens, J.Y. Yu) presented new results on direct photon production in association with heavy quarks.[11] This process can be used to constrain both the heavy quark and the gluon PDF. The γc and γb final states have been studied at the Tevatron; preliminary measurements indicate the bottom channel appears to agree well with predictions, while there is an apparent discrepancy in the charm process at high p_T . Curiously, this is what one might expect if there were an intrinsic charm component in the PDFs. Figure 4-b) displays the predictions for $p\bar{p} \rightarrow \gamma c$ without any intrinsic charm, and with two intrinsic charm (IC) models (BHPS IC and Sea-like IC); the intrinsic charm PDF component appears to yield better agreement between data and the predictions. A more complete analysis of the Tevatron data is in progress, and studies involving LHC data will soon be available. Additionally, this process has the potential to be one of few processes that can help constrain the largely unconstrained nuclear gluon PDF in pA collisions at the LHC.

A. W. Jung (on behalf of the H1 collaboration) presented new results on D^* production in DIS at low Q^2 . This analysis increased the phase space in η and p_T of the measurements, and compared these results to different theoretical predictions.[12] Specifically, the Zero Mass (ZM) calculation failed to adequately describe the data while the massive HVQDIS program (based upon the $g \rightarrow Q\bar{Q}$ process) generated a reasonable description. With this expanded η and p_T there were some regions at the limit of the kinemat-

ics where the HVQDIS model differed from the data. It will be interesting to see if an improved theoretical analysis can yield improved comparisons in this region. This differential measurement is also used for determining the charm contribution to the proton structure. As this measurement yields largest phase space coverage, and thus smallest errors at low Q^2 for this kind of measurement, it has a strong impact on the HERA combined $F_2^{c\bar{c}}$ extractions.

EXPERIMENTAL ISSUES:

Open Charm and Beauty Production, Quarkonia and spectroscopy

At this conference we have seen a wealth of new results on charm and beauty quark production. For the first time results in hadroproduction are available from LHC but also new DIS and photoproduction results were released from HERA. In general the description of all these measurements by the massive scheme NLO predictions is reasonable, with some exceptions in certain phase spaces corners. New TEVATRON results were presented on quarkonia, there are still both experimental and theoretical puzzles, in particular in the area of polarisation. BELLE and BABAR showed new interesting spectroscopy results for quarkonia and on excited charm mesons. The results mentioned in the following subsection are only (hopefully) representative samples from selected talks. Many more interesting results can be found in these and the other working group session talks to which no explicit reference is given here.

Open Charm and Beauty Production

Production in DIS at HERA: New measurements on the structure function $F_2^{b\bar{b}}$ were presented by ZEUS [13], [14], using electrons in the final state or based on a secondary vertex tag. The compilation of all available HERA results is shown in Fig. 5 (left). The description by the various theory predictions is reasonable.

Production in Photoproduction at HERA: Figure. 5 (right) shows an updated summary plot for the beauty production measurements in photoproduction at HERA as function of the beauty quark transverse momentum. Two new measurements were included: The first one from H1[15] extends the range to lower transverse momenta (down to about 2 GeV) than ever covered before at HERA. The second result from ZEUS[16] adds precise points at large momenta (up to 30 GeV). The summary plot demonstrates that the massive scheme NLO calculation can describe the HERA data over the whole kinematic phase space reasonably well.

Charm and beauty hadroproduction at LHC: Despite the low luminosities recorded and analysed at the time of this conference, an impressive amount of charm and beauty hadroproduction results was already presented by the LHC experiments. ATLAS [17] showed first charm meson production results which were compared with different NLO

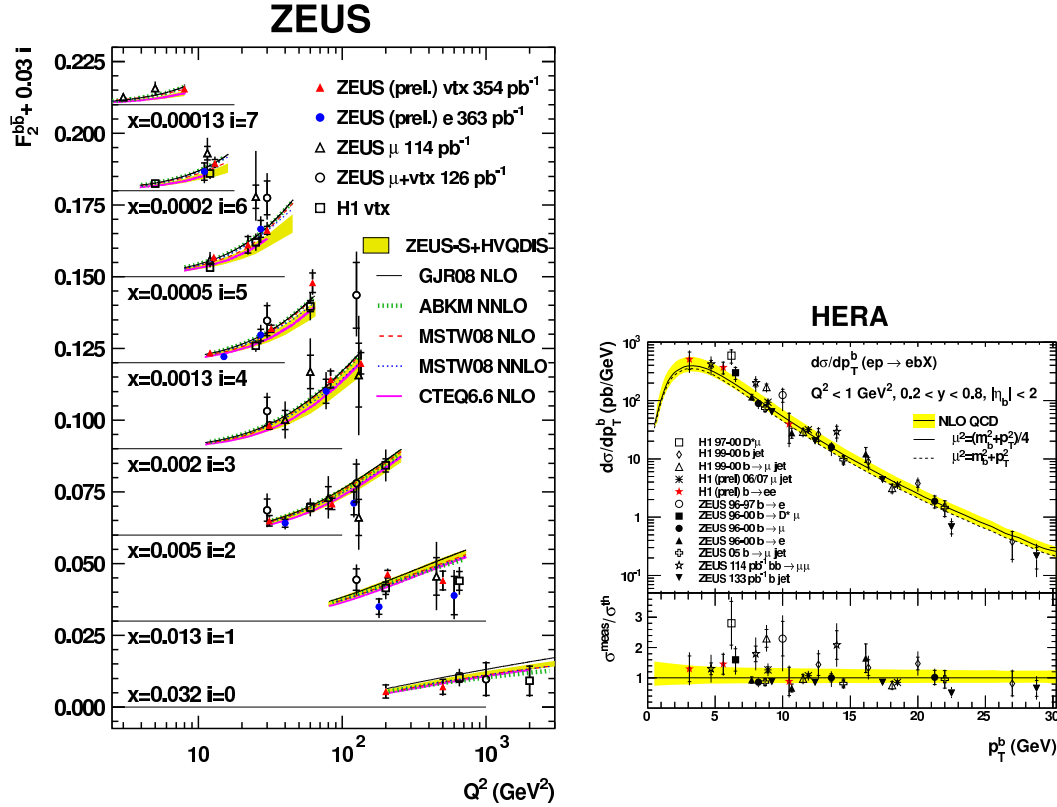


FIGURE 5. Left: Compilation of $F_2^{b\bar{b}}$ results from H1 and ZEUS compared to various predictions. Right: Comparison of H1 and ZEUS beauty measurements in photoproduction to a NLO prediction.

calculations which are able to describe the data within the theory uncertainties. So far the data are restricted to transverse momenta up to 40 GeV, but with the much more data already recorded one can expect in the future very interesting extensions to much higher momenta. LHCb [18] showed (Fig. 6) differential cross sections for D^0 production versus transverse momentum in several bins of rapidity, in the typical forward rapidity range (2-4.5) covered by the apparatus. Both ATLAS [19] and CMS [20, 21] have presented measurements of beauty jet production as function of the jet transverse momentum in bins of rapidity (see Fig. 7). Again the description by NLO calculations is reasonable, at high p_T the MC@NLO predictions overshoot the CMS data in the not so central rapidity ranges. CMS [22] has also studied beauty-beauty angular correlations. The gluon splitting $g \rightarrow b\bar{b}$ is expected to give the dominant contribution. The description by different models is not perfect. ALICE [23] has presented measurements of charm plus beauty cross sections tagged with muons measured in the ALICE forward muon spectrometer. Also here the description by the prediction (FONLL) is fairly good. The future of all the LHC open charm and beauty measurements is bright: more statistics and in particular kinematic phase-space extensions to much higher scales will be possible.

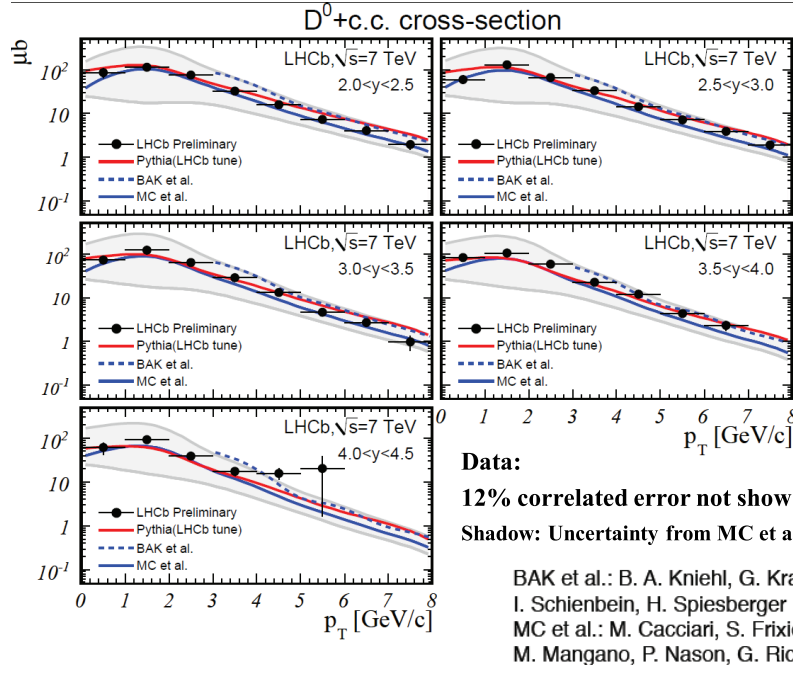


FIGURE 6. D^0 production results from LHCb.

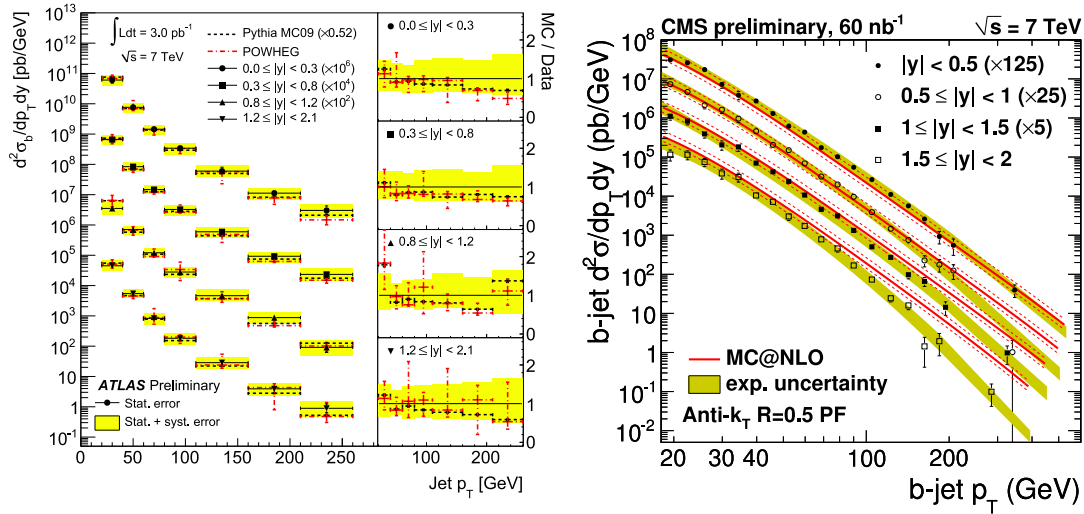


FIGURE 7. Beauty jet production measurements by ATLAS and CMS.

Quarkonia production

In this subsection we will review talks from LHC, TEVATRON and HERA on inelastic J/Ψ production. Quarkonia production at hadron colliders is theoretically not settled. Most models fail to simultaneously describe measurements of both cross section and polarisation. Prompt J/ψ cross section measurements have been presented by

CMS [24]. They exceed expectations in the forward region at small p_T . Measurements of Upsilon(1s) production from LHCb and CMS were presented in the talk [25]. LHCb provides a nice extension to the forward regions. A Good agreement at high p_T between the CMS data and NRQCD (non relativistic QCD) prediction was reported. ZEUS [26] presented J/ψ photoproduction cross sections at HERA, double differential as function of p_T and the energy fraction z which the J/ψ takes from the photon in the proton rest frame. These data will provide important input for global fits with the NRQCD approach. Upsilon(1S) polarisation measurements from CDF and D0 are largely inconsistent, as presented in the talk [27]. However, one difference is that they measure in different rapidity regions. The CDF J/ψ polarisation measurements are not well described by neither NRQCD nor kT-factorisation calculations. In summary, there are still both experimental and theoretical puzzles in the area of quarkonia polarisation.

Charm and Beauty Spectroscopy

Charmonium spectroscopy is an exciting topic as pointed out in the talk [28]. There are several states, recently discovered, that are non-compliant with the $q\bar{q}$ hypothesis. An Example for this is the $X(3872)$ state. Various ideas exist for exotic charmonium-like states, e.g. tetraquark models, hybrids and others. LHCb measurements of the masses of $X(3872)$ and for beauty ground states mesons/baryons were presented in the talk [29], the latter one being already the world best. The h_b members of the bottomonium family were searched for by Belle as reported in the talk [30]. Prominent peaks are observed and mass values were determined for the 1P and 2P states. BABAR results on h_b were reported by [28] and the mass value of the 1p state was measured. As summarised by Leo Piilonen: B factories have made surprising studies of new states in charmonia/bottomonia, but more studies and more data are needed to reveal their true nature. New results have been also presented on the excited charm meson spectroscopy, by BABAR [31] and ZEUS [32]. In these studies BABAR has discovered new states which are attributed to be radial excitations.

Heavy Flavor in Heavy Ion Collisions

At this conference, the two RHIC collaborations, STAR and PHENIX, and the ALICE collaboration at the LHC, presented measurements of multi-particle correlations involving a heavy flavor parent as well as measurements pertaining to the interaction of J/ψ and Υ mesons in the medium produced in heavy ion collisions.

PHENIX [33] showed two-particle correlations of electron-muon pairs in d+Au and $p + p$ collisions coming predominantly from decays of open charm mesons. Back-to-back $e - \mu$ pairs are suppressed in d+Au collisions relative to $p + p$ collisions. Along these same lines, the STAR experiment [34] presented a measurement of correlations between an electrons from charm and bottom decays and a hadron in d+Au and $p + p$ collisions. The back-to-back $e - h$ correlation as a function of the azimuthal angle between the pairs is seen to be broadened with respect to the distribution in $p + p$,

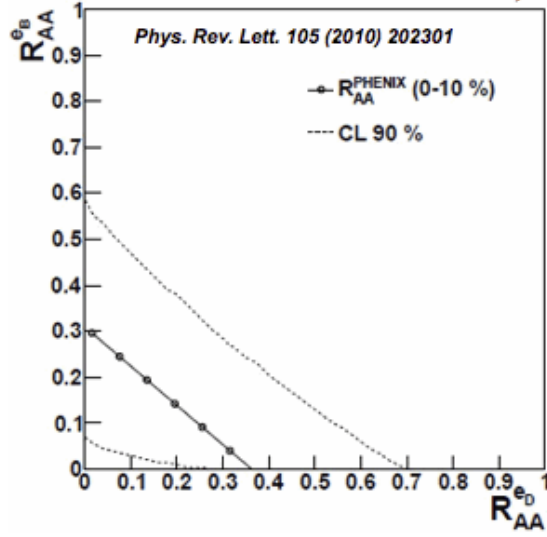


FIGURE 8. 90% confidence level contours for the nuclear suppression factor of open B and D mesons, using non-photonic electron R_{AA} measurements from PHENIX and electron-hadron correlations from STAR.

similar to that seen in di-hadron correlations. Using $e - h$ correlations as well as data from the PHENIX experiment, STAR was also able to put an upper limit of about 0.6 with 90% confidence level on the nuclear suppression factor R_{AA} of open bottom mesons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Figure 8 shows the 90% confidence level for the D and B meson suppression.

The PHENIX collaboration [35] presented measurements of the suppression of Υ mesons at low x in the di-muon channel, as well as high precision measurements of R_{AA} for J/ψ mesons at forward at mid-rapidity. STAR [36] showed a proof-of-principle result on a correlation between Υ mesons and unidentified hadrons, which could be used to measure the radiation emitted off of a colored heavy quark pair during production. The ALICE experiment [37] presented early results on J/ψ production through the di-electron and di-muon channels.

Top Quark Production

CDF, D0, ATLAS, and CMS presented improved measurements of the top quark mass and production cross sections. Results on top quark charge and asymmetry between t and \bar{t} masses were also presented.

The CDF collaboration [38] excluded the top quark charge of $-4/3$ with a 95% confidence level. This presentation also showed an initial look at W boson polarization, measured to be consistent with standard model predictions. D0 [39] presented the most precise result in the dilepton channel of the top quark cross section $\sigma_{t\bar{t}}$, which was measured to be $7.4^{+0.9}_{-0.8}$ pb. D0 also measured the t-channel cross section to be consistent with the standard model. The same collaboration also presented their most precise top

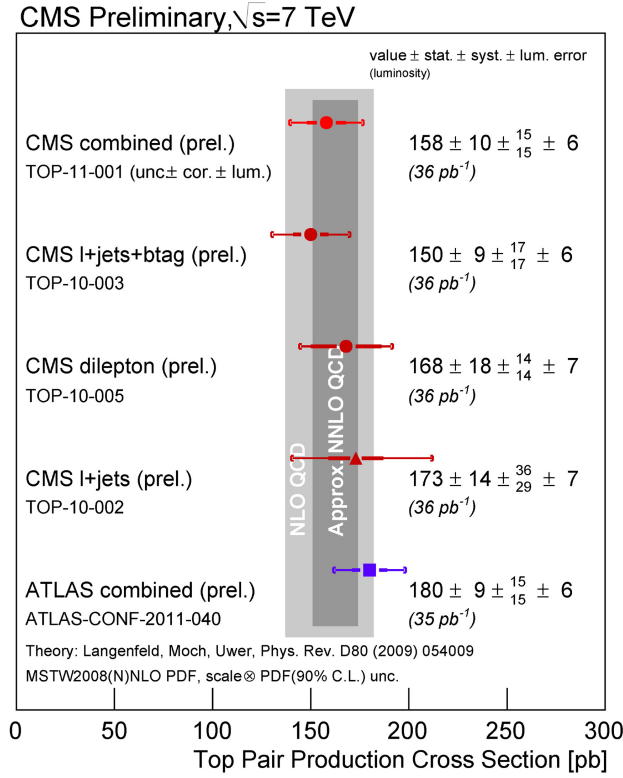


FIGURE 9. ATLAS and CMS measurements of the top quark cross section.

quark mass measurement to data [40], as well as a measurement, consistent with zero, of the mass difference between the top and anti-top quarks.

The ATLAS collaboration presented a measurement of the top quark cross section at 7 TeV by tagging a b -jet and measuring 1-lepton and 2-lepton rates [41], and also showed a measurement of the top quark mass using 3 complementary techniques [42]. CMS [43] showed measurements of the top quark cross section from 3 methods, as well as a measurement of the top quark mass in the dilepton channel [44]. Figure 9 shows the cross section measurements from LHC and ATLAS. CMS [45] also showed t -channel cross section results with 36% precision, consistent with the standard model.

Rare Searches

D0 [46], CDF [47], ATLAS [48], and CMS [49, 50] showed many results of new physics searches involving top quarks. The closest any of the results came to showing an inconsistency with the standard model was the measurement by CDF of the $t\bar{t}$ rest frame asymmetry in 2σ excess over the standard model prediction. Other results set limits on masses of new particles, such as the limit set by D0 on the mass of a fourth generation quark to be below 285 GeV/ c^2 with a 95% confidence level.

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